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Alerting, Orienting and Executive Control: The effects of sleep deprivation

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Abstract

Sleep deprivation has been shown to alter attentional functions, like sustaining an alert state over a period of time (vigilance or tonic alerting). However, the effects of sleep loss on both orienting and executive control are not still clear, and no study has assessed whether sleep deprivation might affect the relation among these three attentional abilities. In this study we used the Attentional Network Test (ANT) in order to investigate the efficiency of the three networks: alerting, orienting and executive control. Eighteen right-handed male subjects participated to the experiment, which took place on two consecutive days. On the first day, in order to evaluate baseline condition, the subjects performed the ANT; on the second day, during 24 h of sleep loss, the same task was performed two times, at 5.00 p.m and at 4.00 a.m. Results showed an overall slowing of reaction time in the nocturnal session, indicating a decrease of vigilance. The orienting network influenced the executive function network in a positive way (the flanker effect was smaller for spatial cue than for the other type of cues). However, results did not confirm an effect of sleep deprivation on both executive control and orienting systems, suggesting the independence between the tonic component of the alerting and the other two attentional systems.

Keywords: Attention Network Test; Sleep Deprivation; Validity Effect; Congruency Effect; Alerting Effect

Introduction

The behavioural and cognitive effects of total sleep deprivation (TSD) are well-known (Hill, 2004). TSD increases sleepiness and affects performance on cognitive tasks (e.g., Sagaspe et al., 2006). These aspects are very relevant for understanding the consequences of sleep loss as the cognitive demands of work increase, and night work becomes more frequent.

Performance deficits can occur during the first night without sleep, and are amplified after two nights (e.g., Horne & Pettit, 1985; Monk & Carrier, 1997). Concerning higher cognitive functions, executive tasks are likely to be sensitive to TSD, such as planning, decision making, judgment, reasoning, speech and divergent thinking (Harrison, Horne, Rothwell, 2000; Killgore, Balkin, Wesensten, 2006; Nilsson et al., 2005). For instance, neuropsychological test, such as word fluency tasks (Harrison et al., 2000), and the “Stroop task” (Lingenfelser et al., 1994; McCarthy & Waters, 1997), are sensitive to one or two nights of sleep deprivation, as well as both error detection and error remedial actions (Tsai et al., 2005), detection of novelty (Gosselin, De Koninck, Campbell, 2005), or shifting between simple cognitive tasks (Heuer et al., 2004) are impaired by TSD. Equally, decision making under conditions of uncertainty, may be particularly vulnerable to sleep loss (Killgore, Balkin, Wesensten, 2006). Specifically, sleep deprived subjects take more risk than they ordinarily would when they were considering a gain, but less risk than they ordinarily would when they were considering a loss (Mckenna et al., 2007). In summary, TSD appears to particularly compromise cognitive functioning mediated by the frontal lobes.

Within the functions that suffer from one night of total sleep deprivation one of the most prominent seems to be attention; in fact it is usually recognized that performance decrements after sleep loss are mainly due to attentional deficits (Dinges, 1992), an explanation that consider attention like an unitary construct. On the contrary, cognitive researchers agree upon the idea that attention is a multidimensional ability (Fan, Raz, Posner, 2002; Posner & Petersen, 1990), that it is possible to consider concretely as an organ system (Posner & Raz, 2004). This system involves almost three specialized neural networks and neuromodulators, subserving different attentional functions: 1) Alerting, defined as achieving (phasic alerting) and maintaining (tonic alerting or vigilance) a general state of activation of the cognitive system. 2) Orienting, that selectively allocates the attentional focus to a potentially relevant area of the visual field; 3) Executive Control –i.e., the ability to control our own behaviour in order to achieve intended goals and resolving conflict among alternative responses.

It is well-known that TSD affects the alerting system, as reflected by reaction time tasks (Urrila et al., 2007; Van den Berg & Neely, 2006). However, due to many inconsistent results, effects of sleep loss on both orienting and executive
control are not still clear. Regarding orienting, few studies have addressed this issue using a Covert Attention Task (Posner, 1980). In this task, spatial orienting can be manipulated by presenting a spatial cue, which comes before target presentation, and can be either valid or invalid with regard to the target location. A valid cue indicates the location of the target, while in the invalid cue condition, the target appears in a position not indicated by the cue. Generally, reaction times (RT) in the valid condition are more rapid than RT in the invalid condition; this effect is known as attentional orienting effect.

Studies evaluating the relation between the decrease of vigilance and orienting have lead to contrasting results (Casagrande et al., 2006; Fimm, Willmes, Spijkers, 2006; Versace et al., 2006). Specifically, Casagrande and co-workers (2006) found a general decrease in arousal (a significant increase in RT) across 24 h of sustained wakefulness, but not a selective effect on the orienting mechanisms. On the contrary, Versace at al. (2006), using a partial sleep reduction paradigm, observed a significant slowing down of RT in the reorienting mechanism (invalid condition). A similar interaction between alerting and orienting was found by Fimm et al. (2006); in their study, subjects performed a covert attention task every four hours, during a 28 hours period of prolonged wakefulness; their results indicate a significant increase of RT for invalid trials only in the left visual field. One of the most relevant differences among these studies concerns the type of manipulation used to measure the orienting process; in fact, an interaction between the two systems was observed in the two studies (Fimm et al., 2006; Versace et al., 2006) that used a peripheral predictive cue, but it was not found by Casagrande et al. (2006), who used a central cue; in other words, orienting and alerting networks seems to interacts when the subject has to perform a task activating especially bottom-up components of attention. This agrees with the finding showing an increased orienting effect under phasic alertness, when peripheral non-predictive cues are used (Callejas et al., 2004; 2005).

In relation to the executive control system, although many studies found TSD impairs executive functions (Gosselin et al., 2005; Harrison et al., 2000; Heuer et al., 2004; Killgore et al., 2006; Lingenfelser et al, 1994; McCarthy & Waters, 1997; Mckenna et al., 2007; Nilsson et al., 2005; Tsai et al., 2005), other studies do not confirm any impact of TSD on executive control. For instance, Binks, Waters and Hurry (1999) showed that short-term sleep deprivation have no effects on a Stroop task, a Wisconsin Card Sorting Test and a word fluency task. In agreement with these results are those found by Fallone, Acebo, Arnedt, Seifer and Carskadon (2001), who did not observe an impaired performance in inhibition tasks following sleep reduction. Equally, Sagaspe et al. (2003) found no effects of 36 h of sleep loss in a short task requiring random letters generation.

Based on these contrasting data, it seems needed to evaluate the effects of a moderate sleep deprivation on the attentional networks, utilizing a single task that manipulate at the same time alerting, orienting and executive control. To this purpose, we have chosen a task developed by Fan et al. (2002), named Attention Network Test (ANT). This task results by a combination between a covert attention task (Posner, 1980) and a flanker task (Eriksen & Eriksen, 1974). Visual stimuli are used to separately assess alerting (improved performance following a warning non spatial cue), orienting (an additional benefit when the cue correctly indicate the target location), and executive control functions (impaired performance when the target contains conflicting information).

The ANT was used for several reasons: 1) It is a brief (20 minutes) and simple task. This factor is remarkable considering the non-univocal results about the impact of sleep deprivation on the executive functions (Harrison et al., 2000; Sagaspe et al., 2003). Particularly, the question could be the following: does the impairment of the executive system depends from a larger sleep deprivation (i.e., longer than 24 hours and, therefore, implying a stronger reduction of alertness), or from the use of longer and complex tasks, which does it should selectively act on the executive system? If these are the determining elements, we might suggest for an efficient executive control in the ANT during 24 hs of continuous wakefulness.

2) The ANT allows appraising the relationship between the attentional systems (independence/interaction). The independence was confirmed for adult subjects (Fan et al., 2002) and children 7 years old (Rueda et al., 2004). Although an interaction between the executive and the other networks seems to be well established, the interaction between alerting and orienting is not valuable in the ANT, cause the type of cues presented that did not allow an independent measure of two systems. In fact, it has been observed (Callejas, 2004; 2005; Fuentes & Campoy, 2008) that when alerting is increased by introducing a warning stimulus, the orienting and alerting systems interact. Accordingly, a paradigm of sleep deprivation can be interesting, not only to verify its effects on the attentional functions, but also to appraise the relationship between orienting and alerting, when this last is manipulated in an independent way. In this case, at variance with other studies (Callejas, 2004; 2005; Fuentes & Campoy, 2008), we have manipulated tonic, and not phasic alerting.

METHODS

Subjects

Eighteen males (mean age: 23 ± 2.6) signed an informed consent before participating as volunteers in the study. The study was approved by the local ethical committee. They were all naive to the purpose of the experiment and all of them reported normal or corrected to normal vision. During the experimental session, subjects did not drink or eat anything containing caffeine and similar (e.g., tea, chocolate).

Apparatus, Stimuli and Procedure

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Stimuli were programmed and presented via software E-Prime on a Pentium 4 computer, presenting to a 21-inch colour VGA monitor. Responses were collected through the keyboard of the computer.

For an extensive and detailed description of both stimuli and procedure see Fan et al. (2002) study. Stimuli consisted of a row of five horizontal black lines, with arrowheads pointing leftward or rightward presented on a grey background. The target was a left- or right-pointing arrow at the centre, which was flanked on either side by two arrows pointing either in the same direction (congruent trials), or in the opposite direction (incongruent trials), or by lines (neutral trials). A single arrow or line subtended 0.558° of visual angle. The target and flankers were presented 1.06° above or below the fixation point. The participants’ task was to identify the direction of the centrally presented arrow by pressing a button with the index finger of the right hand for the right direction and another button for the left direction. Target buttons were counter-balanced among subjects.

Each trial consisted of these events: a fixation period of variable duration (400 – 1600 msec), a cue presented for 100 msec, and the target display, which was presented 400 msec after the cue. The target and flankers were presented until the subject responded or until 1700 msec. Each trial lasted for 4000 msec. The fixation point appeared at the center of the screen during the whole trial. While congruency between target and distracting arrows’ direction was used to measure the executive control network; four cue conditions were used to measure efficiency of alerting and orienting networks: no cue (baseline), center cue (cue at fixation), double cue (one cue at each of the two possible target position), and spatial cue (a cue 100% predictive of the target location). After a 24 trial practice block, subjects performed three experimental blocks. Each one consisted of 96 trials.

**General Procedure**

The experiments were run on two consecutive days. On the first day participants came individually to the laboratory during the morning and they performed the task, for training. On the second day, after subjects slept their usual 8 hrs, they were kept awake for 24 hours. The task was performed at 5.00 p.m. (Baseline: BSL) and at 4.00 a.m. (Sleep Deprivation: S-DEP).

**Experiment Design**

The following dependent variables were considered: the mean RT, the *validity effect* (central cue RT - spatial cue RT), the *alerting effect* (no-cue RT - double cue RT), and the *congruency effect* (incongruent trials RT - congruent trials RT). On mean RT, a *Session* (BSL, S-DEP) x *Cue* (Spatial, Central, Double, No-cue) x *Flanker* (Congruent, Incongruent, Neutral) repeated measures ANOVA was performed. For evaluating the efficiency of the attentional systems, an one-way ANOVA considering the factor *Session* (BSL, S-DEP) was performed on *validity*, *alerting* and *congruency* effects, separately. For *post hoc* analysis of the means, the Duncan test was used.

**RESULTS**

All RT less than 100 ms or longer than 1400 ms were excluded. These represented 0.34% of trials. The error rate was 2.30% of the trials.

The ANOVA performed on mean RT showed a significant effect for *Session* ($F_{1,16}=27.91; p<0.001$), with higher RT in the S-DEP session (Mean RT: 565.67 ms), as compared to BSL (Mean RT: 506.18 ms). The main effect of *Cue* ($F_{3,48}=51.48; p<.00001$) was also significant and *post hoc* analysis revealed faster RT in the spatial cue (Mean RT: 500.38 ms), as compared to either no-cue (Mean RT: 571.49 ms; $p<.00005$), double cue (Mean RT: 532.31 ms; $p<.001$), and central cue trials (Mean RT: 539.52 ms; $p<.001$); further, RT were faster in both double cue ($p<.001$) and central cue trials ($p<.001$) than in no-cue trials. The main effect of *Flanker* ($F_{2,32}=129.57; p<.0000001$) was significant and the Duncan test showed slower RT for incongruent trials (Mean RT: 591.61 ms) as respect to both congruent (Mean RT: 508.91 ms; $p<.0001$) and neutral trials (Mean RT: 507.25 ms; $p<.001$). No difference was found between congruent and neutral trials ($p=.78$). The *Cue x Flanker* interaction was also significant ($F_{6,96}=21.41; p<.0001; Figure 1), and *post hoc* analysis showed a significant congruency effect for each type of cue (all $p<.001$); higher RT in no-cue trials compared to all the other cue types ($p<.001$) were observed for the congruent condition. In the incongruent condition, rapid RT were present in spatial cue trials as respect to all the other cue types ($p<.001$). In the condition with neutral flankers, longer RT were present in the no-cue trials compared all the other types of cue ($p<.0002$); while, no difference in RT were found among spatial, central and double cue conditions ($p=20$). The ANOVA did not show any other interaction: *Session* by *Cue* ($F<1$), *Session* by *Flanker* ($F_{2,32}=2.71; p=.08$) and *Session* by *Cue* by *Flanker* ($F_{6,96}=1.54; p=.20$).

![Figure 1](image_url)  
**Figure 1.** Mean RT for every flanker condition as a function of the cue type.

The ANOVA on the validity effect showed no variation between the two sessions ($F<1$), while the *Session* was significant for the *alerting effect* ($F_{1,16}=1.54; p=.03$), with a great result in nocturnal (Mean RT: 34.84 ms) as compared to diurnal hours (Mean RT: 23.11 ms). Finally,
The Session was near to significant ($F_{1,16}=3.76; p=.07$) for the congruency effect (Figure 2).

![Validity effect](image1)

![Alerting effect](image2)

![Congruency effect](image3)

**Figure 2.** Variations of alerting, orienting and congruency effects as a function of the session type.

**DISCUSSION**

Results confirm that the experimental paradigm adopted in this study was able to produce an effective increase of RT during the nocturnal session (4.00 a.m.), according to other studies adopting the same experimental manipulation, i.e. a 24 hours of prolonged wakefulness (e.g., Casagrande et al., 2006). The efficacy of the task used was also confirmed, as indicated by both validity and congruency effects. On the contrary, no effect of vigilance decrease on orienting mechanisms was observed, in line with Casagrande et al. (2006) study. This result could be due to the absence of invalid cues in the ANT and, consequently, to the lack of information about the reorienting mechanisms, that resulted impaired in other studies (Fimm et al., 2006; Versace et al., 2006). The absence of this interaction could be due to other characteristics of the ANT, as the short duration of the task and the use of a fixed SOA. These features could have made the task very easy for allowing it to affect both orienting and executive control. This conclusion is in line with other results showing an independence of orienting from orienting when a short and easy Covert Orienting Task was used under a sleep deprivation condition (Casagrande et al., 2006).

However, other authors using a short and easy Covert Orienting Task under a sleep loss condition observed a significant slowing down of RT in the reorienting (invalid condition) mechanisms (Versace et al., 2006). A similar interaction between alerting and orienting was found by Fimm et al. (2006), but only in the left hemisphere. One of the most relevant differences among these studies concerns the type of manipulation applied to the orienting process; in fact, an interaction between the two systems was observed in both studies (Fimm et al., 2006; Versace et al., 2006) that used a peripheral predictive cue, but it was not found by Casagrande et al. (2006), who used a central cue; in other words, the attentional systems apparently require an interaction between orienting and alerting when the subject has to perform a task activating bottom-up components of attention. In order to systematically analyze the interaction between alerting and orienting, a recent study (Casagrande & Martella, 2008) considered both the role of the employed cue and the intensity of the induced decrease of alertness. In this study, three different Covert Orienting tasks respectively using a highly informative peripheral cue or two different type of central cue (a digit vs. an arrow) were administered under a TSD paradigm within two temporal windows characterized by different levels of vigilance. Results revealed that another variable appears to affect the interaction between alerting and orienting, this is the intensity of alertness. In fact, the interaction between the two attentional systems was effective only when a mild decrease of vigilance was induced by sleep deprivation, while alerting and orienting resulted independent when both a high or a very low level of vigilance was considered. This relation, not considered by previous studies (Casagrande et al., 2006, Fimm et al., 2006; Versace et al., 2006), could account for the independence between alerting and orienting founding in this study, in which sleep deprivation session was characterized by a strong decrease of vigilance.

In line with other studies (Binks et al., 1999; Fallone et al., 2001; Sagaspe et al., 2003; 2006), results did not confirm an effect of sleep deprivation on the executive control system. In this case, is very hard to suggest an explanation able to account for the different results observed by many authors. In fact, many executive functions are found to be sensitive to sleep loss (i.e., Gosselin et al., 2005; McKenna et al., 2007; Nilsson et al., 2005; Tsai et al., 2005), but other studies did not confirm any effect (Binks et al., 1999; Fallone et al., 2001; Sagaspe et al. 2003).

One could suggest that in order to observe a significant impairment of executive functions, a stronger decrease of vigilance could be needed, in other words, twenty-four hours of continuous wakefulness could be able to induce only a mild and not significant (p=.07) worsening of executive functions. In line with our hypothesis, conflict resolution could be more difficult when a sleep deprivation of great duration (i.e., longer than 24 hours and, therefore, with a stronger reduction of alertness) is adopted, and/or when a longer task is used. On the contrary, a moderate TSD and a short task could have only a strong effect on the alerting system, but it could be too much weak to induce a a significant impairment of the executive control.

The different results through the studies could also affected by the type of the task employed for assessing the executive functions. A Flanker task could be fairly simple.
and the performance could be not affected by TSD, as well as that required by a Gambling task (Killgore et al., 2006).

However, another hypothesis could be advanced, in our study the reduction of vigilance due to TSD could have been compensated by the increase of phasic alerting elicited by the visual cues. Specifically we have observed, like Fan et al. (2002), a strong alerting effect for the spatial cue, which permit participants to direct their attention to the target stimulus area, reducing the influence of the surrounding flankers.

Of course, the lack of any effect of sleep deprivation on the Flanker task performance used in this study could seem amazing. In fact, sleep loss would have had to compromise high cognitive functions, as well as executive control, mediated by the frontal lobes (e.g., Robbins, 1998). As a matter of the fact, a mild sleep deprivation (i.e., 24 hours of continuous wakefulness) causes a decrease of metabolic activity in frontal cortex, thalamus, and striatum (Wu et al., 2006), as well as in prefrontal areas (Thomas et al., 2000), that are associated to poorer performance on complex cognitive tasks (Thomas et al., 2003). However, when sleep deprived, subjects showed a compensatory response to their reduced performance ability; in fact, the impairment in RT, under sleep deprivation, appears related with a greater activation in the frontal and posterior midline cortical regions (Drummond et al., 2005). Equally, a poor performance on a divided attention task appears to be associated with an increased activation in the bilateral prefrontal cortex and parietal lobes (Drummond & Brown, 2001), particularly in the right hemisphere (Drummond, Gillin, Brown, 2001).

In conclusion, based on behavioural results and on PET data, one could hypothesize that the contrasting results on tasks evaluating executive functions could be due to the type of task used for evaluating the executive functions or from the extension of sleep deprivation, but the things don’t seem go in this way. As a matter of the fact, an impairment in the Stroop test was observed under both 24 hours (Lingenfelser et al., 1994) or 36 hour (McCarthy & Waters, 1997) of continuous wakefulness, but this result was not confirmed by other authors (Binks et al., 1999). Specifically, our results are in line with those of previous studies (Hsieh, Cheng, and Tsai, 2007; Murphy et al., 2006), which found no impairment in a flanker task performed by sleep-deprived subjects. At the same time, our results differ from other findings showing an impairment in both RT and response accuracy in a flanker task performed after one night of sleep deprivation (Tsai et al., 2005).

In order to explain these inconsistent results, a further hypothesis can be advanced. When sleep deprivation causes a high reduction of vigilance, i.e., when attentional performance is evaluated in a time window corresponding to the primary sleep gate, all the attentional functions are equally impaired, so it is hard to find selective effects on executive functions or on orienting. In this condition, the high inter-subjects variability to TSD effects (Banks & Dinges, 2007), could, at least partly, account for many experimental incongruent results found in TSD studies. As a matter of the fact, neurobehavioural deficits from TSD vary significantly among individuals and are stable within individuals (Van Dongen et al., 2004). Based on a vast review of sleep deprivation research, Banks & Dinges (2007) suggested a trait-like differential vulnerability to sleep deprivation. In line with this hypothesis it was found that, after 48 h of sleep deprivation the de-activation of a neural network, including posterior cerebellum, right fusiform gyrus, precuneus, left lingual and inferior temporal gyri, was effective only in subjects showing an impairment in memory performance, but not in those able to maintain higher performance (Bell-Mcguity et al., 2004). This variability in neural and behavioural responses to TSD, in conjunction with the intensity of vigilance decrease produced by TSD, could account for many contrasting results in this research area.

References


